Anaerobic Baffled Reactor and Hybrid Anaerobic Baffled Reactor Performances Evaluation in Municipal Wastewater Treatment

Mohammad Aqaneghad*[1], Gholamreza Moussavi[1], Reza Ghanbari[2]

1) Department of Environmental Health Engineering, Faculty of Medical Sciences Tarbiat Modares University, Tehran, Iran
2) Department of Environmental Health Engineering, School of Health, Qazvin University of Medical Science

**Author for Correspondence:* mamamaxy01@yahoo.com

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ABSTRACT

This work investigated the performance of an anaerobic baffled reactor (ABR) and a hybrid ABR (HABR) for the treatment of municipal wastewater (MWW) under ambient conditions and compared the ability of the two systems to meet effluent discharge standards.
The reactors were studied under hydraulic retention times (HRTs) of 48, 36, and 24 hours and effluent recycling (ER) rates of 0.25-1. The startup success was determined by the COD removal efficiency. The startup lasted for 107 days. In steady state COD removal efficiency decreased from 91.4% using a 48-hour HRT to 83.5% using a 24-hour HRT in the ABR, while the COD removal efficiencies of the HABR were 2.2% greater than those of the ABR at all HRTs. The HABR met COD and BOD_5 effluent discharge standards using a 36-hour HRT, while the ABR achieved these standards only with a 48-hour HRT. Using a 36-hour HRT, the HABR total nitrogen (TN) and total phosphorus (TP) removal efficiencies were 14.9% and 26.6%, while those of the ABR were 1.3% and 1% lower, respectively. The ABR and HABR met both the TSS and TP effluent standards using 48- and 36-hour HRTs, respectively, but neither met the TN effluent standard. ER did not have a positive effect on the total efficiency of either reactor. The HABR was found to be suitable for conventional MWW treatment, particularly in small cities and on-site treatment facilities.

Key words: Anaerobic Baffled Reactor, Municipal Wastewater Anaerobic Treatment, Hybrid Anaerobic Baffled Reactor

INTRODUCTION

Extensive use of natural resources has led to severe Anaerobic wastewater treatment has gained considerable attention among researchers and sanitary engineers primarily due to its economic advantages over conventional aerobic methods. The major advantages of anaerobic wastewater treatment in comparison to aerobic methods are: (a) the lack of aeration, which decreases costs and energy requirements; and (b) simple maintenance and control, which eliminates the need for skilled operators and manufacturers. Among high-rate anaerobic reactors, the ABR appears to be promising for wastewater treatment [1].

MC Carty *et al.* developed an ABR that is comprised of a series of up-flow anaerobic sludge blanket reactors. As indicated by its name, this system consists of a series of vertical baffles that force the wastewater to flow under and over them while passing from the inlet to the outlet. The bacteria within the reactor tend to rise and settle with gas production and up-flow velocity in each compartment; their horizontal movement is relatively slow [2]. Thus, the wastewater experiences an opportunity to come into closer contact with a considerable amount of active biomass as it passes through the ABR. This approach has numerous advantages over other reactors, including longer biomass retention times, better resilience to organic and hydraulic shock loading, considerable removal of soluble microbial products, the ability to integrate with the aerobic phase inside the system, and exceptional ability to partially separate various phases of anaerobic catabolism [3]. However, this system is notorious for its lower-quality effluent. The removal of nitrogenous pollutants is particularly difficult for these bioreactors [4]. Thus, development of the ABR, which needs neither a sludge blanket nor granular and flocculent biomass due to its configuration, was undertaken. Recent studies have shown the ability of the ABR to successfully manage wastewater [4-5]. Therefore, recent research has focused on improving the performance of the ABR while using its exceptional characteristics in the treatment of municipal wastewater. One of the major alterations suggested for enhancing ABR performance is the integration of a fixed-bed microbial process [6]. Thus far, few studies have been investigated the treatment of MWW by ABRs (see Table 3), and no research has been performed on the HABR under filed conditions.

The purpose of this study was to evaluate and compare the performance of the ABR and HABR in the treatment of MWW at different HRTs and effluent recycling (ER) rates under ambient conditions, with the goal of meeting effluent discharge standards.

MATERIALS AND METHODS

Reactor setup

Two bench-scale ABR reactors were fabricated of black Plexiglas sheets and installed at the Khoy Wastewater Treatment Plant porch site in Iran under ambient conditions. The reactors consisted of five equally-sized chambers. The effective, or net, volume of the reactors was measured using the filled water volume. A schematic of the reactors is shown in Fig. 1 and reactor dimensions and characteristics are presented in Table 1. The rector design was based on previous similar studies. The tops of the reactors were covered and a valve was installed to vent biogas. The reactors were fed with screened municipal wastewater using two calibrated peristaltic (Etatron) pumps with variable speeds. The reactor effluent was collected in a closed tank and discharged daily. The reactors were equipped with three inlet and outlet ports to distribute the influent equally throughout the width of the reactors and minimize the dead space. At the conclusion of the installation phase, one of the reactors was converted to an HABR. The ABR was the source reactor. The reactors differed only in the existence of media in the HABR.

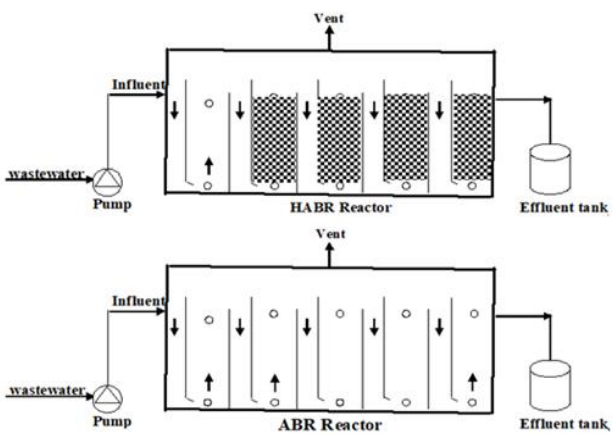


Fig. 1: schematic of the reactors

Sampling and analysis

Combined 24-hour sampling was used due to fluctuations in the quality of the MWW and the effluent of both reactors. Samples were collected three times per week from the reactor inlets, reactor outlets, and the sampling ports of all compartments. The total samples number was 800. Samples were collected on a daily basis (i.e., every 24 hours), preserved in a refrigerator. Analysis of the outlet samples yielded the overall efficiency of the reactors, while analysis of samples from the chamber ports indicated the performance of the individual chambers at steady state under each HRT. Grab samples were collected sequentially from the individual chambers at each HRT. Parameters such as pH, suspended solids (SS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), SO_4, total phosphorus (TP), and total nitrogen (TN) were measured using standard methods. SS, BOD_5, COD, TP, and TN were determined using the 2540D, 5210B, 5200-D, 4500-5, and 4500N analytical methods, respectively [7]. Chemical materials from the Merck and Hatch companies were used during the experiments. A DR5000 HACH spectrophotometer was used to determine component concentrations, and Microsoft Excel software was used to analyze the data. Data averaged over the steady state in each stage were used in the graphs shown herein.

Table 1: Reactor design parameters

Dimension	Size
Length	60 cm
Width	27 cm
Height	30 cm
Up-flow/down-flow	3:1
Total volume	48.6 L
Effective volume	37 L
Microbial medium	HDPE-2H
Media specific surface	535 m^2/m^3

Reactor startup and experimental procedures

Before beginning experiments, the reactors were troubleshot and examined for water-tightness. Then, the reactors were inoculated with seed sludge, which had total and volatile suspended solids (TSS and VSS) concentrations of 8.6 and 4.42g/L, respectively, and a pH of 7.5. The seed sludge was acquired from a local anaerobic wastewater treatment plant. The raw MWW used to feed the reactors was drawn continuously from the canal downstream of the screening and grit chamber units of the aforementioned treatment plant. The characteristics of the wastewater used over the course of the study are shown in Table 2. The reactors were activated after sludge seeding. Throughout the research period, the reactors were fed wastewater continuously by two peristaltic pumps operated in parallel. The HRT was set based on the reactor effective volume. Startup was judged to be complete when changes in the removal of (total) COD remained below 2% for ten consecutive days. Upon startup, the steady-state performance of the reactors was evaluated at HRTs of 48, 36, and 24 hours. After selection of the minimum HRT that met the effluent discharge standard (i.e., the optimum HRT), the effect of the ER ratio was evaluated in order to upgrade the reactor efficiency at an HRT of 24 hours (the minimum HRT). The ER is the ratio of the recycled effluent flow rate to the raw wastewater flow rate; the ER ranged from 0.25

to 1.0. Recirculation was adjusted by the other peristaltic pumps so that the recirculated effluent was mixed uniformly with raw wastewater. The system was considered to be at 'steady state' when changes in the COD removal efficiency remained below 3% for ten consecutive days. After both reactors achieved steady-state performance at the end of the startup period, one reactor was converted into an HABR via the installation of HDPE (high-density polyethylene) microbial media equal to 25% of the reactor effective volume. The 'hybrid' designation on this system indicates the integration of suspended biomass into attached biomass. The media were installed in the third, fourth, and fifth chambers to revive and overcome the methanogenic bacteria present at the end of the reactor. Medium collection at the end of the reactor was caused by unexpelled biomass. The first and second HABR chambers were not filled with media due to the risk clogging resulting from raw wastewater accumulation on the medium. The performance of the reactors was studied at HRTs of 48, 36, and 24 hours and organic load rates (OLR) of 0.28, 0.37, and 0.5kg COD/m^3·d, respectively. The HRT range was selected according to the possibility of meeting the COD standard for effluent discharge into water.

Table 2: Characteristics of the municipal wastewater

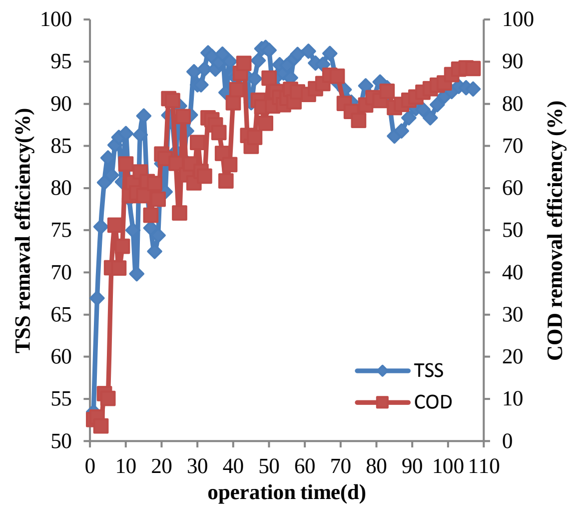
Parameter	Unit	Average
BOD_5	mg/L	361
COD	mg/L	575
SCOD	mg/L	277
TSS	mg/L	258
VSS	mg/L	152
TP-PO_4	mg/L	22.6
pH		7.55
TN	mg/L	69.5
NO_3-N	mg/L	2.6
SO_4	mg/L	75.3
Alkalinity ($CaCO_3$)	mg/L	513
Temperature	ºC	16-26

RESULTS AND DISCUSSION

Reactors startup

Fig. 2 shows the performance profile of the reactors during the startup phase using the average of the data from both reactors. The reactors performed similarly. As can be observed in Fig. 2, after some initial fluctuations, the reactors approached steady-state performance on the 105th day of operation. At this point, startup was considered to be successfully accomplished. After the completion of startup, the averages and standard deviations (SD) of the steady-state removal of TSS, SCOD (soluble COD), and COD were determined to be 93 ± 1, 81 ± 1, and 89 ± 1%, respectively. Effluent COD, SCOD, and TSS concentrations reached 68, 55, and 18mg/L, respectively. During the startup phase, the effluent pH was 7.8, which is the optimum level for methanogenic bacteria. As evidenced by the relatively high and stable SCOD removal, as well as the effluent pH, the system showed clear anaerobic bio-degradation of organic compounds.

Fig. 1: Performance of the reactors throughout the startup period



According to the literature, the startup time generally ranges between 60 and 90 days depending on the climate and wastewater characteristics [8]. The startup period in this study was longer due to diurnal and seasonal fluctuations in raw wastewater and seasonal decreases in wastewater temperature. Due to the alkalinity of the wastewater, the outlet pH was approximately equal to the influent pH. The effluent alkalinity was 11% higher than that of the influent; this pH increase can be explained by the use of volatile fatty acids (VFA), which release carbonate and bicarbonate, and the production of S-2, which is generated by sulfate bio-reduction reactions. The pH fluctuated in all reactor compartments and increased gradually over the length of the reactors. Anaerobic digestion was indicated by an 86% SCOD removal rate and an oxidation reduction potential (ORP) of −320mV at the end of the reactor.

Performance of the reactors at steady state

The effect of HRT on the sectional performance of the reactors

All of the three operational stages were continued until stable COD and BOD removal efficiency maximums were attained. The system was operated at HRTs of 48, 36, and 24 hours for periods of 63, 55, and 40 days, respectively. At the end of each HRT test period, when the COD removal efficiency was stable, the performance of each reactor compartment was determined by measuring the pH, TSS, COD, BOD, TN, TP, SO_4, and NO_3 concentrations in both reactors. Fig. 3 shows the COD removal profiles of the ABR and HABR. According to Fig. 3, the first chamber performed the highest, yielding COD removal values in the ABR of 70.6, 16.1, 7.4, 3.3, and 2.6% of total COD removal (87.8%) in chambers C1-C5, respectively. COD removal in the HABR measured 69.2, 15.4, 9, 4.1, and 2.3% of the total COD removal (89.8%) in chambers C1-C5, respectively. This high COD removal in the first chamber was caused by the 57% TSS removal rate. In the HABR experiment with an HRT of 36 hours, cumulative COD removal in the third chamber was approximately 80%. The baffling effect was not evident at HRTs of ≥ 24 hours, and the organic load primarily entered the initial part of the reactor. Similar results have been reported in other studies concerning baffled reactor treatment of sanitary wastewater [9]. The media-packed HABR compartments removed 15.4% of the COD, 2.2% higher than removal in the corresponding ABR compartments. The horizontal velocity of the wastewater in the reactors measured 5, 6.6, and 10 cm/hour at HRTs of 48, 36, and 24 hours, respectively. The COD removal profiles showed that the performance of the ABR and HABR in processing low-concentration wastewater (such as MWW) with HRTs ≥ 24 hours is largely independent of baffling; furthermore, there was partial separation of the acidic and methanogenic phases. Most of the COD was removed in the first and second chambers due to the plug-flow design of both the ABR and the HABR; the efficiency of the system did not increase significantly in the remainder of the reactor length. The HRTs used herein also induce rapid bacterial growth at the initial part of the reactor, reducing the food supply to microorganisms in the latter parts of the reactor [10].

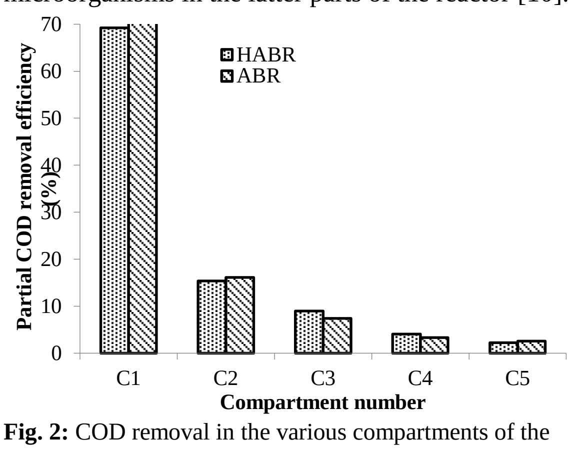


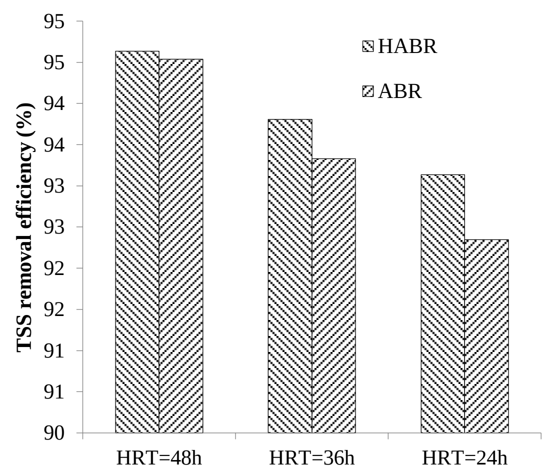
Fig. 2: COD removal in the various compartments of the ABR and HABR using a 36-hour HRT

The effect of HRT on TSS removal

During the steady-state period at the end of each testing stage, the average concentration of the effluent TSS was about 20mg/L for all of the HRTs. The maximum removal (94.6%) occurred using an HRT of 48 hours in the HABR, for which the effluent TSS concentration was 15mg/L. At HRTs of 36 and 24 hours, the TSS removal efficiencies were 93.8 and 93% with effluent TSS concentrations of 18 and 21mg/L, respectively. The TSS removal efficiency became nearly constant, showing no significant variation during the study. Fig. 4 shows TSS removal at every HRT. The amount of TSS removal was approximately constant and independent of HRT; the process of washing aged biomass, leaving only residual biomass attached to the media or flocks that can endure high flow velocity, may cause this stabilization in TSS removal. The reactors met the effluent TSS standard at all HRTs except the lowest, at which the effluent quality deteriorated in terms of colloidal particles and biomass wash-out. The removal of TSS in the HABR was 0.5% greater than that in the ABR, which can be attributed to microbial media acting as a filter. The SS washout resulted from: 1) increasing biogas production, and 2) the release and elimination of biomass, especially in the final compartment. Low levels of sludge, or a lack of sludge, in the last chamber, along with media application, can minimize SS elimination [11].

Fig. 3: Average TSS removal during steady-state conditions

To estimate the amount of active biomass, the concentration of the sludge in all chambers of both

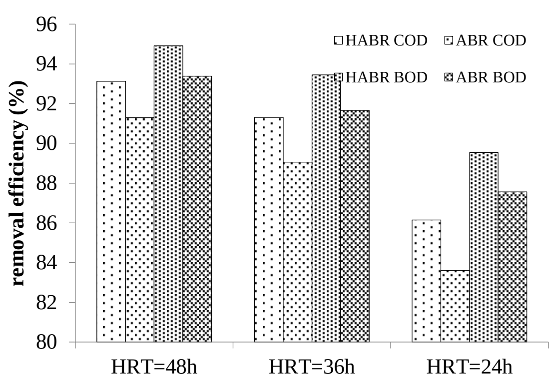


reactors was measured at the end of the research period. Starting from initial amounts of 8.6g/LTSS and 4.42g/LVSS, the sludge concentrations reached 52.1g/LTSS and 27.4g/LVSS on average in both reactors. The maximum sludge concentration was measured in the first chamber, which indicates that the maximum SS removal and microbial growth were also located in this region. The sludge in the first chamber was brown and bulky, while the sludge in the last chamber was black and granular. The microbial mass on the HABR medium measured 1.8 mg/cm^2 of VSS.

The effects of HRT on COD and BOD removal he

COD and BOD removal efficiencies were used to determine system stability and as an index to evaluate performance in terms of effluent discharge standards. At an HRT of 48 hours, the effluent COD decreased to less than 60mg/L in both reactors. At an HRT of 36 hours, the HABR met the discharge standard (COD ≤ 60 mg/L); however, the ABR did not. Fig. 5 shows variations in COD and BOD removal in terms of HRT. The COD and BOD removal efficiencies decreased with decreasing HRT. COD removal in the ABR reached 91.4, 89.1, and 83.5% at the end of experiments with HRTs of 48, 36, and 24 hours, respectively, while COD removal in the HABR reached 93.2, 91.4, and 86.1%, respectively; this indicates that the average COD removal in the HABR was 2.2% more than that in the ABR. BOD removal in the HABR measured 94.5, 93.4, and 89.5% at HRTs of 48, 36, and 24 hours, respectively, while BOD removal in the ABR measured 93.4, 91.7, and 87.6%, respectively. The BOD/COD ratio was 0.62 in the influent and 0.34 in the effluent.

Fig. 4: Average COD and BOD_5 removal under steady-state conditions



SO_4 and NO_3 concentrations were measured during this research to investigate the effects of sulfate-reducing bacteria (SRB) inhabitation on methanogenic bacteria. The average SO_4 removal in the ABR and HABR were 64% and 65.7%, respectively. SO_4 and NO_3 maximum removals were 75% and 41% at an HRT of 48 hours. Removal of NO_3 and SO4 decreased as HRT declined. SO_4 reduction occurred primarily in the initial parts of the reactors (in the acidic phase). Considering information in the literature review [12] and the wastewater COD/SO_4 ratio (7.4), SRB had no significant effect on methanogenic bacteria.

Because O_2, NO_3, and SO_4 gases raise the oxidation-reduction potential, which hinders methanogenic activity, their presence is not favorable in anaerobic wastewater treatment. In addition, SRB compete with methanogenic bacteria for volatile fatty acids (VFAs), which are the preferred food of methanogenic bacteria. Therefore, these materials should be limited in the initial parts of the reactor [13]. Unfortunately, it was not feasible to completely separate the methane production phase from the acid genesis phase in baffled reactors processing low-concentration wastewater. However, the use of more than four baffles improves the efficiency of the reactor and helps methanogenic bacteria dominate the last part of the reactor. In other words, at a constant HRT, the performance of the reactor is improved by increasing the number of appropriately designed baffles.

Stuckey reported irregular removal of COD from sewage in an ABR at high HRTs [2]. Table 3 shows ABR performance in previous similar experiments. According to Table 3, the COD removal efficiency in this study was higher than that measured in previous studies, which may be attributed to the successful extended startup, lower OLR, and high microbial quality in the seed sludge. COD removal in the HABR was 2.2% higher than that in the ABR on average, which can be attributed to 1) the advantages of attached microbial growth in the HABR, such as providing favorable conditions for methanogenic species and higher microbial diversity and density, and 2) the even flow distribution on and larger contact area of the medium surface. Media protect biofilms against washout; therefore, as biomass, and especially methanogen, concentrations increase, the organic matter removal rate increases significantly as well. Generally, the wastewater up-flow velocity in the reactor, sludge bed height, seed quality, biomass concentration, microbial species distribution, reactor design, flow hydraulics (e.g., the equal distribution of influent in the reactor), HRT, and number of compartments all affect the performance of wastewater reactors. When these components are optimized, the removal of organic matter increases substantially [11]. Eighty-five percent of effluent COD was soluble (i.e., SCOD) in both reactors; SCOD is often composed of refractory organic substances such as lignin, tannins, surfactants, microbial metabolic products, and anaerobic decomposition products such as VFA, which are all soluble [9]. COD removal mechanisms include, in order of importance, the conversion of biodegradable materials into biogas, the reduction of sulfate and nitrate, and the physical capture of particulate COD. COD mass balance around the reactors was calculated using Equation (1) [14]:

$$\mathbf{TCOD_{in} = TCOD_{out}\ (COD_{particle.out}+COD_{soluble.out}+COD_{CH4.g}+COD_{CH4.aq}+COD_{biomass}+COD_{SO4})} \quad \text{Eq. (1)}$$

Decreasing the HRT had a significant effect on system performance, especially in the initial part of the reactor. At lower HRTs (24 hours), the decrease in the COD removal efficiency in both reactors can be contributed to the increase in OLR, which affects microbial metabolisms. Indeed, reduced HRTs allow less time for methanogenic bacteria to metabolize the soluble products produced by acid genesis, resulting in soluble product accumulation in the effluent [15]; the reduction in the effective volume in each chamber due to the accumulation of the solids over the course of operation may also contribute.

Table 3: Literature data on ABR performance for domestic wastewater treatment

Influent COD (mg/L)	COD Removal (%)	OLR (kg/m^3 d)	HRT(h)	Reference
501	74 ± 5	1.2	48	[16]
350	86	0.34	6	[9]
716 ± 54.4	72 ± 3	-	22	[17]
906 ± 264	90	2.17	15	[18]
860	68	0.7	3	[1]
300	79	0.7	15	[19]
575 ± 37	91.3	0.28	48	The ABR
575 ± 37	91	0.37	36	The HABR

The effects of HRT on nutrient removal

Fig. 6 shows the changes in TN and TP removal in the reactors. The average concentrations of TN and TP in the effluent were 60 and 17.2mg/L, respectively, in the ABR and 58.9 and 16.8mg/L in the HABR. As shown in Fig. 6, the TN and TP removal efficiencies decreased with reductions in the HRT. The HABR TN and TP removal efficiencies were 21 and 30.2%, respectively, with an HRT of 48 hours, 16.6 and 28.1% with an HRT of 36 hours, and 14.9 and 26.6% with an HRT of 24 hours. The average TN and TP removal efficiencies of the HABR were 1.3% and 1% higher than those of the ABR; this may be attributed to the advantages of attached microbial growth, such as high microbial density, high microbial diversity, and increased contact between the biofilm and the substrate. A COD/N/P ratio of 300/10/1 is needed for anaerobic bacteria, and the influent N/P=12/1.3, while the effluent TN/TP=3.5; according to these data, P was consumed in higher proportion than was N, and the removal efficiency of N was influenced by the HRT. In contrast, the TP concentration did not appear to vary with the HRT.

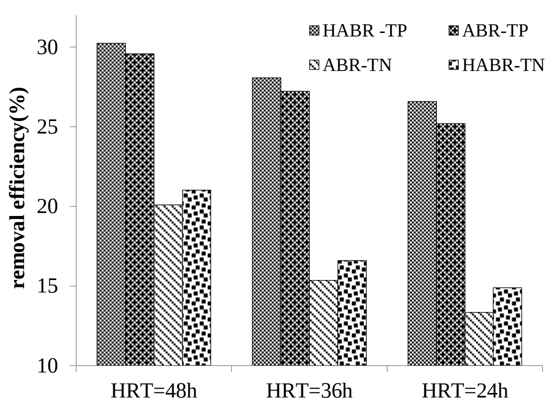


Fig. 5: Average TP (as PO_4) and TN removals under steady state conditions

Nitrogen compounds, and especially organic nitrogen in raw wastewater, are converted to NH_4. During anaerobic biodegradation, 98% of effluent nitrogen was in the form of NH4; a small amount of NH4 was absorbed by biomass, and some portion was expelled without change. In a completely anaerobic environment, there are two nitrogen removal mechanisms: the escape of ammonia and cellular synthesis. Because less than 5% of ammonia nitrogen is in the form of NH_3 (most of it is in the form of NH_4), only 2% escapes in the form of ammonia; cellular synthesis is the major nitrogen removal mechanism [20]. Absorption and cellular synthesis are the two chief phosphorus removal pathways; the rate of biomass absorption exceeds that of cellular synthesis [21]. Our results demonstrated that the effluent TP concentration was relatively stable and that the TN/TP ratio was lower than the constituent N/P ratio of living cells (which was 5-7). Because of insufficient nutrient removal, the reactor effluent should be further remediated with an aerobic or physicochemical post-treatment or other appropriate approach such as algal nitrogen removal or phytoremediation [22].

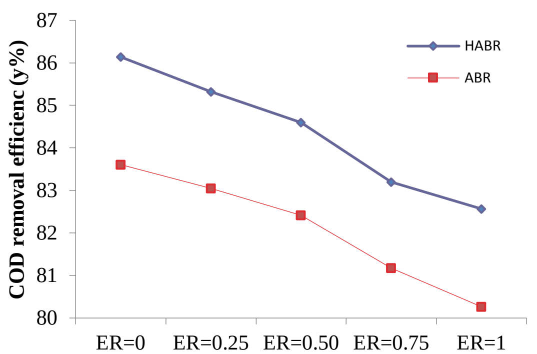
The effect of effluent recirculation (ER) on reactor performance

Fig. 7 depicts reactor performance at various ER ratios at an HRT of 24 hours. Increased ER did not, in fact, improve the effluent quality, but instead had a slight adverse effect. In the HABR, COD removal corresponding to ER rates between 0.25 and 1 were 85.6, 84.6, 83.3, and 82.5%, respectively. The ABR COD removal was approximately 2% less than that of the HABR. ER may affect reactor performance through various mechanisms including dilution of the influent, which affects the quantities of organic and toxic compounds and adding alkalinity for better pH control [23]. In this case, because the influent consisted of a low-concentration municipal wastewater with no toxic materials, effluent recycling did not have a significant effect on reactor performance. The slight reduction in reactor performance due to the ER rate increase can be attributed to the dilution of the influent, which leads to slower microbial metabolisms. Effluent recycling decreases the HRT, increases the OLR, and exacerbates biomass washout; it also destroys the micro-sites containing symbiotic bacteria. ER also disrupts the separation of the acidic and methane phases, increasing methanogenic activity inside the reactor due to the high VFA content in the effluent [24]. Therefore, ER variation did not improve reactor performance.

Fig. 6: The effect of effluent recirculation (ER) on reactor performance at HRT 24 hours

CONCLUSION

The reactors met the TSS effluent discharge into



surface water standards at all HRTs. The HABR met effluent COD, BOD, and TP standards at an optimum HRT of 36 hours, but the ABR met the standard only with an HRT of 48 hours. The TN concentration in the effluent was above the standard at all HRTs for both reactors. Therefore, the HABR is an efficient and appropriate system for municipal wastewater treatment, especially in developing countries. The nutrient-rich effluent produced by the HABR can be reused in agricultural irrigation where it is not in direct contact with human beings or subsurface irrigation.

ETHICAL ISSUES

Ethical issues such as plagiarism have not been observed by the authors.

CONFLICT OF INTEREST

There were no conflicts of interest.

AUTHORS' CONTRIBUTION

The magnitude of each author's contributions is reflected in the author order.

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